

Airborne Use of Traffic Intent Information in a Distributed Air-Ground Traffic Management Concept: Experiment Design and Preliminary Results

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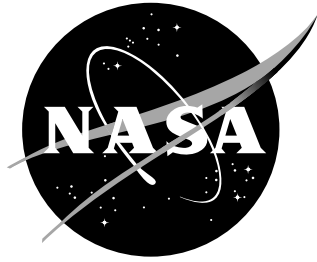
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Abstract

A predominant research focus in the free flight community has been on the type of information required on the flight deck to enable pilots to "autonomously" maintain separation from other aircraft. At issue are the relative utility and requirement for information exchange between aircraft regarding the current "state" and/or the "intent" of each aircraft. Trajectory predictions based on this information are used in the detection of possible losses of separation or "conflicts," and accurate conflict detection capability is a key requirement for autonomous aircraft operations. Investigation of separation assurance in constrained operations may lead to a system-level determination regarding the advisability of exchanging both state and intent information to enable the human participants to achieve all objectives and meet all constraints with long-term stability and safety. Relevant operational constraints include traffic flow management requirements, airspace hazards, aircraft performance limitations, and operational economic considerations.

This paper presents the experimental design and some initial findings of an experimental research study designed to provide insight into the issue of intent information exchange in constrained en-route operations and its effect on pilot decision making and flight performance. The piloted simulation was conducted in the Air Traffic Operations Laboratory at the NASA Langley Research Center. Two operational modes for autonomous operations were compared under conditions of low and high operational complexity. The tactical mode was characterized primarily by the use of state information for conflict detection and resolution and an open-loop means for the pilot to meet operational constraints. The strategic mode involved the combined use of state and intent information, provided the pilot an additional level of alerting, and allowed a closed-loop approach to meeting operational constraints. Potential operational benefits of both modes are illustrated through several scenario case studies. Subjective data results are presented that generally indicate pilot consensus in favor of the strategic mode. Pilot comments presenting merits and criticisms of the operational modes are included, as are usability assessment ratings for user-interface design features.

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Abbreviations

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|----------|--|
| ADS-B | Automatic Dependent Surveillance - Broadcast |
| ASTOR | Aircraft Simulation for Traffic Operations Research |
| ATC | Air Traffic Control |
| ATM | Air Traffic Management |
| ATOL | Air Traffic Operations Laboratory |
| ATSP | Air Traffic Service Provider |
| CDTI | Cockpit Display of Traffic Information |
| CDU | Control and Display Unit |
| CNS | Communications, Navigations, and Surveillance |
| DAG TM | Distributed Air/Ground Traffic Management |
| FCP | Flight Control Panel |
| FL | Flight Level |
| FMS | Flight Management System |
| MCP | Mode Control Panel |
| NAS | National Airspace System |
| NASA | National Aeronautics and Space Administration |
| ND | Navigation Display |
| NLR | National Aerospace Laboratory of The Netherlands |
| PFD | Primary Flight Display |
| PredASAS | Predictive Airborne Separation Assurance System |
| RTA | Required Time of Arrival |
| SUA | Special Use Airspace |
| TCP | Trajectory Change Point |
| TFM | Traffic Flow Management |
| TMX | Traffic Manager |

Introduction

A large portion of the aviation user community has identified a need for increasing flexibility of aircraft operations while retaining guaranteed separation from hazards. This need has been expressed as a new operational paradigm, “free flight,” which reduces reliance on centralized air traffic management. Free flight is defined by the RTCA Task Force 3 as a safe and efficient flight operating capability under instrument flight rules in which operators have the freedom to select their path and speed

in real time¹. One approach to achieving mature-state free flight is to distribute responsibility and capability for traffic management between aircraft and ground-based air traffic control over as much airspace as possible, while minimizing the mandating of equipment for airspace access.

A significant research activity within the NASA Aviation System Capacity program is focused upon far-term operations of the National Airspace System (NAS). A general description of the activity is *Distributed Air/Ground Traffic Management* (DAG TM). DAG TM is based on the fundamental premise that all NAS participants can be both information suppliers and users, thereby enabling collaboration and/or distribution in all levels of traffic management decision making. Successful operation in this new environment will be achieved through new human-centered operational paradigms enabled by procedural and technological innovations. These innovations include decision-aiding automation, information sharing, and communication, navigation, and surveillance / air traffic management (CNS/ATM) technologies.

In planning for the DAG TM research activity, NASA has developed a high-level DAG TM concept of operations consisting of 15 elements spanning gate-to-gate operations². One particular DAG TM concept element developed to address the en-route flight regime (Concept Element #5) has the potential to increase capacity, flexibility, and robustness of the NAS by distributing responsibility for 1) separation assurance and 2) conformance with local traffic flow management (TFM) constraints between airborne and ground-based systems. In this concept element, pilots of aircraft designated as “autonomous” have the authority to generate and implement new trajectories at their discretion in order to meet individual-, company- (if applicable), and/or system-level goals. They also have the responsibility for separation assurance and compliance with local TFM constraints established by the ground-based air

traffic service provider (ATSP). Aircraft not operating as autonomous aircraft are designated as “managed aircraft,” and similar to current operations, their flight crews comply with clearances provided by the ATSP, who maintains responsibility for separation assurance and flow management conformance of these aircraft.

Information Requirements Research

A predominant research focus in the free flight community has been on the type of information required on the flight deck of autonomous aircraft to enable their pilots to ensure separation from other aircraft. Accurate detection of “conflicts” or predicted loss of separation between aircraft is a key requirement for autonomous aircraft operations. At issue are the relative utility and requirement for inter-aircraft information exchange of the current “state” (three dimensional position and velocity vector) and “intent” of each aircraft; this surveillance information forms the basis for trajectory predictions used in automated conflict detection. Additionally, related human factors issues exist, such as determining how pilots would use the surveillance information and how this information should be presented on the flight deck displays, considering usability, display design precedence, and integration with other pilot tasks.

Previous research has indicated that, under unconstrained operations (no schedule or airspace restrictions), the exchange of state information between aircraft is sufficient to safely enable airborne self separation in the en route domain³. A state-only system has the potential to significantly reduce bandwidth requirements for future surveillance systems such as Automatic Dependent Surveillance - Broadcast (ADS-B), and it reduces the complexity of conformance monitoring and conflict alerting logic. To address the conflict alerts missed by not using intent information, Hoekstra et. al.³ developed and tested a predictive airborne separation assurance system (PredASAS) that calculates potential off-

trajectory conflicts by comparing the current state vectors of traffic aircraft to *possible* changes of the own-ship (i.e., subject aircraft performing self-separation) state vector. Own-ship maneuvers that would result in traffic conflicts are displayed as avoidance bands on the heading, airspeed, and vertical speed indicators. This system was designed to provide information regarding which maneuvers would lead to a conflict without the crew needing to “probe” or “try various maneuvers.” The conclusion was made that “if all equipped aircraft are fitted with PredASAS, there is no longer a need to know intent information because nobody will turn (or climb/descend) into a conflict.”³

In contrast, a study conducted at the NASA Ames Research Center suggested that pilots nevertheless preferred to be provided traffic-aircraft intent information, and the preferred source of intent information was Flight Management System (FMS) flight plan data⁴. In this study, flight crews were alternately provided with three types of traffic information: state data, Mode Control Panel (MCP) data, or FMS data. The flight crews were given the opportunity to use voice communication channels to communicate directly with other aircraft to gather intent information or negotiate resolutions. Results of the study indicated that pilot preferences for intent information centered primarily on the improved ability to understand the conflict alerts. Intent information type (state, MCP, or FMS) was found to have no effect on separation assurance.

Operational Constraints

Little research has been performed on the feasibility of *constrained* operations. Constrained operations are important to consider in concept feasibility and viability analyses, because operational constraints ultimately limit airspace capacity (notwithstanding runway availability limitations), and a concept that does not address capacity limitations is of little practical interest. It is in the more highly constrained conditions that operations will be

found to be either fragile or robust to real-world system demands and variability.

Operational constraints can generally be expressed in four categories: flow management, airspace hazard, performance, and economic. These four categories of constraints, together with constraints provided by complex traffic geometry and dense traffic volumes, must be considered in the assessment of autonomous operations feasibility.

Flow management constraints are restrictions that must be imposed to make sure traffic flow through the airspace is as high as possible. Examples of such constraints in the current system are speed and altitude restrictions at fixes and speed restrictions en route in order to regulate the flow of aircraft, for example, into capacity-limited terminal airspace. In a future system, the ATSP may be able to transmit the scheduled time of arrival to an aircraft and allow the flight crew to incorporate this constraint as a “required time of arrival” (RTA) in their trajectory planning. This type of constraint puts time pressure as well as positional endpoint requirements on the current segment of flight.

Airspace hazard constraints are present when certain regions of airspace are inadvisable for entry. Examples of such airspace hazards are active special-use airspace (SUA) and convective weather cells. The former constraint is proscribed by the ATSP or aeronautical databases, and the user (company or pilot) generally proscribes the latter constraint based on safety. Regardless, the pilot must take these airspace restrictions into account when defining conflict resolution strategies.

Performance constraints include restrictions based primarily on the operating limitations of the aircraft. Restrictions such as maximum operating altitude, speed, or climb/descent rate govern the degrees of freedom available for conflict resolution maneuvers.

Economic constraints include user-generated operational guidelines that must generally be

met a majority of the time for a commercial aviation business to remain viable for the long term. Examples include fuel efficiency, schedule considerations, and passenger comfort.

When constraints of these types are considered in combination with the task of separation assurance, the type of traffic surveillance information provided to the flight crews may play a more critical role in their ability to repeatedly and reliably meet their separation assurance responsibility than in unconstrained operations. This issue extends beyond the *minimum requirement* for information that enables airborne separation assurance, and it extends beyond the *preferences* of the flight crew. The study of constrained operations is critical to determining the overall *advisability* of exchanging intent information to enable the participants of future distributed-responsibility operations to achieve all objectives and meet all constraints with long-term stability.

This paper presents the design and some preliminary findings of an experimental study designed to provide insight into the issue of intent information exchange in constrained en-route operations. In the experiment, two modes of autonomous aircraft operation, tactical and strategic, were tested for comparison. Both modes have been proposed as viable alternatives in the constrained, en-route, operational environment described earlier. The *tactical mode* is primarily characterized by minimal information exchange, i.e., state information only. The *strategic mode* features the exchange and use of both state *and* intent information. Additional important distinctions between these modes exist and are described in detail in “Modes of Autonomous Operation.” Sixteen active line pilots each flew a simulated aircraft through four en-route scenarios: the two modes of operation within two levels of operational complexity. In these scenarios, the pilots encountered traffic conflicts and operational constraints of the types described earlier. Automated conflict management tools (for conflict prevention, conflict detection, and

conflict resolution) were provided as appropriate to each operational mode. The pilots were instructed to resolve traffic conflicts and simultaneously meet the operational constraints. Data acquired for analysis included objective measures related to trajectories flown, the pilot's manipulation of the display features, the timing of conflicts and maneuver decisions, and pilot workload. Subjective measures of workload and pilot assessments of display features and concept feasibility were also acquired. The experiment was conducted in the NASA Langley Air Traffic Operations Laboratory, a medium-fidelity workstation simulation of airspace operations.

Modes of Autonomous Operations

Two modes of autonomous operations have been proposed as viable alternatives for free flight. They differ from each other in several respects, beyond just the level of information exchange.

Tactical mode

The tactical mode has been developed and investigated over several years in batch and piloted simulation studies by the NLR (National Aerospace Laboratory of The Netherlands)³, and it is primarily characterized by simplicity in several respects. Its design attempts to minimize the requirements placed on supporting technology, including both data link and pilot decision-support automation. Broadcast data-link bandwidth requirements are minimized by employing conflict detection based only on the current aircraft state vector (current position, altitude, ground track, ground speed, and vertical speed). On-board conflict detection algorithms deterministically compare (in the current implementation) the state vector of traffic aircraft with that of the own-ship. To minimize false alerts associated with extrapolation errors⁵, state-vector-based conflict detection is limited in its "look ahead" time horizon. The research of NLR determined that 5 minutes was sufficient for separation assurance, and so a 5 minute look-ahead horizon was used in the current study for state-based conflict detection.

If a conflict (i.e., predicted loss of regulatory separation) is detected, the pilot is alerted to the event and the conflict resolution algorithm is automatically activated to calculate maneuver advisories for the pilot. These conflict resolution advisories are simple in that they are recommended changes to the own-ship state vector (i.e., change in track, ground speed, or vertical speed). The pilot implements the maneuver by setting heading, airspeed, or vertical speed targets in the Flight Control Panel (FCP) to match the advised settings. This procedure is comparable to the pilot's current use of the FCP to comply with a vector for traffic issued by Air Traffic Control (ATC). Concurrently, a conflict prevention system (i.e., PredASAS, described earlier) monitors all possible single-dimensional maneuvers for conflicts, and it indicates to the pilot what maneuvers shall not be made to prevent new conflicts from occurring, essentially a "no-go" alerting system. All maneuvers outside of the displayed no-go bands are conflict-free for at least the next 5 minutes, assuming the traffic aircraft do not maneuver during this time.

The resolution maneuvers in this operational mode are tactical in nature because they only resolve the conflict and do not account for a return to the original flight plan or the consideration of external constraints such as RTAs or airspace hazards. This highlights the primary characteristic of the tactical mode, that of the open-loop (manual) nature of meeting constraints. It is hypothesized that the pilot would typically solve problems sequentially: first – resolve the conflict by maneuvering clear; second – avoid any nearby airspace hazards; third – develop an efficient plan to return to course; fourth – make adjustments to meet RTA and other ATC constraints. This approach has the effect of spreading decision-making over time and possibly simplifying the maneuver decisions. After maneuvering safely to resolve the original conflict, the pilot monitors the PredASAS information to determine when it is safe to return to course.

Strategic Mode

The strategic mode is a closed-loop (automated) method of trajectory planning. Any trajectory changes implemented by the flight crew will have been determined a priori to meet all known constraints and optimization criteria while both solving the current problem (e.g., a detected conflict) and returning the aircraft to course. This approach places greater demand on decision-support automation in that it must generate trajectories for pilot review based on a simultaneous solution of constraints and objectives. To ensure that the entire modified portion of the flight plan will be conflict free, the automation must have a longer look-ahead time horizon to be aware of future changes in traffic-aircraft state vectors. The intended trajectory or “intent” of each aircraft is therefore included in its broadcasted data-link message, and greater demands are correspondingly placed on the data link bandwidth to accommodate the additional information. For this experiment, the intent message was defined to be a series of trajectory change points, although other forms of intent are acknowledged to also be pertinent and are currently being studied⁶.

Conflict detection is typically performed using both traffic state information and traffic intent information. The state-based conflict detection in the experiment was identical to that in the tactical mode with a 5-minute look-ahead horizon. The intent-based conflict detection deterministically compared the own-ship flight plan to the traffic-aircraft broadcast intent in a search for intent conflicts⁷. Whereas a 15-20 minute look-ahead horizon is thought to be appropriate for intent-based conflict detection, a shorter horizon of 8 minutes was used in the current study allowing more data runs to be accomplished during the limited availability of the subject pilots.

A conflict-alerting decision algorithm was developed to determine when and how to alert the pilot to potential and actual conflict situations where state and intent data are both used for detection. The utility of combining

state-based and intent-based conflict detection is that it allows the alerting system to distinguish between a full-fledged conflict alert that requires own-ship action, and a situation that should be resolved by the traffic aircraft. The latter situation would require no own-ship action but would have the potential for elevating to the former category. Events where this could occur include failure of either aircraft to observe priority and/or maneuver flight rules (described below) or an unannounced deviation from the broadcast intentions (i.e., intent non-conformance). It is hypothesized that distinguishing within the alerting logic between situations that require or do not require own-ship action should reduce unnecessary maneuvering and therefore improve overall system stability. The alerting logic is described in more detail later in “Flight Deck Display Design.”

In contrast to the tactical mode, the strategic mode takes advantage of existing technology on the flight decks of many commercial aircraft for conflict resolution, in particular the FMS because it contains a detailed database of the aircraft performance characteristics and operating limitations. By coordinating the conflict-resolution calculations with the flight planning and trajectory generation functions of the FMS, a complete re-planning of the local trajectory can be performed that guarantees that the new trajectory is within the flight envelope. In addition, the FMS can also be used to close the loop on ATSP constraints. Speed and path strategies that meet an RTA at a downstream fix or airspace boundary can be incorporated into the proposed conflict-resolution trajectory. Resolution strategies can also incorporate predicted locations of convective weather cells and scheduled activation of special-use airspace or any region that would be considered hazardous or inadvisable to enter, assuming this information was made available to the aircraft systems (which may require additional flight-deck and ground-based functions). Since the solution space that meets these constraints would normally be large, trajectory optimization can be performed to achieve a desired goal, such as fuel economy, a comfortable ride, or an early

arrival. The FMS can then be used to fly the complete resolution trajectory, potentially reducing the workload of the flight crew.

Conflict resolution advisories for conflicts based on valid intent (i.e., the intruder aircraft is determined to be conforming to its broadcast intent) were calculated using a genetic-algorithm-based optimization routine⁸. This routine was designed to iterate trajectory constraints with the FMS until a conflict-free trajectory that meets all additional constraints (e.g., RTA) is determined. Further iterations are then performed to optimize a selected parameter (e.g., fuel-burn minimization). The trajectory would normally be flown by the FMS. For conflicts requiring own-ship action that are based on state information, resolution advisories identical to those in the tactical mode are presented. These advisories are flown by the pilot using the FCP.

Flight Rules for the Strategic Mode

Two types of flight rules are envisioned for the strategic mode of operation, each providing a distinct benefit. A *maneuver flight rule* is one that governs what types of maneuvers are not permissible in certain situations. The strategic mode incorporates a maneuver flight rule that is designed to prevent near-term conflicts from suddenly appearing. The same rule was applied to the tactical mode, as described earlier in the use of the PredASAS alerting system. The rule states that an aircraft may not implement a change in track, speed, or vertical speed that creates a near-term conflict (for the current study, within 5 minutes). The pilot would meet the requirements of this rule by avoiding flight in the direction of a PredASAS band, although transition through a band is permitted. This maneuver flight rule has the additional benefit of providing some predictability of autonomous-aircraft operations, which should aid the ATSP in developing stable strategies for managed-aircraft separation.

A *priority flight rule* defines which aircraft in a given conflict situation is responsible for

resolving the conflict. The tactical operational mode has no priority flight rule in that it assumes every autonomous aircraft shares equal responsibility to resolve conflicts, which is prudent given the short time horizon for detecting and resolving conflicts. The strategic operational mode also assigns equal responsibility for near-term conflicts (defined for the current study as 5 minutes). However for conflicts more than 5 minutes away, the conflict geometry is used to determine a “right-of-way” priority, such that one aircraft must give way to the other. By assigning resolution responsibility to one aircraft in a conflict pair, predictability should increase, total maneuvering at the system level should decrease (ideally by one-half since only one aircraft maneuvers), and system-level traffic flow stability may be enhanced. For conflicts detected significantly far in advance (perhaps greater than 15 minutes – a subject of future research), the benefits of assigning responsibility are likely to disappear, and therefore priority flight rules would no longer be applied. The application of flight rules as a function of time is shown in figure 1.

Flight Deck Display Design

A new cockpit display of traffic information (CDTI) design concept, exercised in the strategic mode for this experiment, was developed to address the issues of effectively integrating (rather than superimposing) state and intent information for conflict detection into a single presentation. The design, summarized below, was built on state-only and intent-only display features previously developed by NLR³ and NASA Ames Research Center⁹. The aircraft simulation used in the current experiment was a representation of the MD-11 aircraft. The new display features for autonomous operations were therefore integrated into the MD-11 flight-deck display suite, and existing MD-11 conventions were adhered to as much as possible. The Primary Flight Display (PFD) and Navigation Display (ND) were the only displays affected. An ND control panel was added, and its use is described below.

CDTI Design Features

The new display design follows the common approach of superimposing traffic data on the ND. The ND with some of the CDTI features is shown in figure 2. An unfilled chevron symbol represents the position and track angle of a traffic aircraft relative to the own-ship. A short, protruding stinger indicates the aircraft is operating in autonomous status, and the absence of the stinger represents managed status. The symbols are color encoded for at-a-glance relative altitude information: blue for aircraft above the own-ship; green for aircraft below; and white for same altitude within ± 1000 ft. Attached to the base of each chevron is the altitude value in 100s of feet; the pilot is able to select whether absolute or relative altitude is shown using a button on the ND control panel. An up or down arrow is also shown if the climb/descent rate exceeds 100 feet per minute. Through the ND control panel, the pilot is able to filter the display of aircraft (for de-cluttering) that are outside a pilot-selectable vertical range. Pilots could input values from ± 2000 feet to $\pm 40,000$ feet, or they could turn the filter off and display all aircraft within the horizontal range selected. Horizontal range display information could be varied from 320 nautical miles to 10 nautical miles. To simulate airborne broadcast datalink range limitations, only information from aircraft within 120 nautical miles were received and displayed.

Additional information is available to the pilot for either all aircraft on the display or just individual aircraft. For all aircraft, the pilot can select to display the call sign next to each chevron. The pilot is also able to display the state vector extending in front of the chevrons for pilot-selectable lengths representing from 2 to 20 minutes of flying time. For any single aircraft, the pilot is able to select additional information to be displayed, including: a data block showing call sign, absolute altitude, target altitude (if available), and ground speed; the path representing the broadcast intent (if available); and the protected zone to be avoided for separation assurance.

The display design incorporates the PredASAS conflict prevention system. This system consists of “no-go” indications in the form of color-coded bands on the ND compass rose, the PFD vertical speed scale, and PFD airspeed tape. The bands indicate which instantaneous changes to the aircraft state vector would result in a state conflict. An amber color indicates a loss of separation would occur in less than 5 minutes, and a red color indicates a loss in less than 3 minutes. To identify which aircraft is causing the band, the pilot uses a point-and-select device (the computer mouse for the current desktop simulation experiment) to select the band on the ND compass rose. A circle representing the protected zone of the aircraft is displayed for 3 seconds. For aircraft outside the vertical filter setting, the aircraft and its protected zone are displayed for 3 seconds despite the filter.

Conflict Alerting

For conflict situations, the alerting of the flight crew uses an approach that is similar to the MD-11 convention for aircraft system alerts. The alerting logic is based on three levels of alerting, and the symbology is shown in figure 3.

A Level 1 alert is used when information must be conveyed to the pilot, but no action is required. The symbology for a Level 1 alert is a change in the traffic-aircraft chevron color to amber, with the chevron remaining unfilled. This alert level is used primarily in two situations. In the first situation, a state conflict is detected, but no intent conflict is detected (i.e., the aircraft is planning to change course or altitude before losing separation). If both aircraft are determined to be conforming with their broadcast intent, then no action is required other than to continue to monitor for intent conformance. In the second situation, an intent conflict is detected, but the priority flight rules decree that the own-ship has priority and the traffic aircraft must maneuver. Again, no action is currently required, and the traffic aircraft is “pointed out” to the own-ship pilot. The Level 1 alert may be useful in “priming” the pilot for

potential blunder situations that would elevate the alerting to Level 2. Note that Level 1 alerts only occur in the strategic mode.

A Level 2 alert requires action by the own-ship flight crew. The alert is used when a conflict has been detected, and it is the responsibility of the own-ship flight crew to resolve the situation. The symbology for a Level 2 alert has two components separated in time. When the conflict is first detected, an aural alert is given, and the traffic aircraft symbol changes to a filled, amber chevron. The predicted position of the traffic aircraft at the time of loss of separation is shown with a circle representing its protected zone. The flight plan or state vector is shown in amber between these two symbols. If the time to loss of separation is less than 3 minutes, additional alerting text and a countdown time is shown on the ND, as well as an additional aural alert.

A Level 3 alert requires *immediate* action by the own-ship flight crew. This alert corresponds to the actual loss of separation. The symbology for a Level 3 alert is a red filled chevron for the traffic aircraft, plus an aural alert.

Conflict Resolution Advisories

The detection of a conflict triggers the calculation of a resolution advisory by the decision-support automation, and the proposed trajectory is sent directly to the FMS. The proposed trajectory is displayed on the ND for pilot review. As a temporary measure, conventional symbology for an alternate route is used for the proposed trajectory. The calculation and display of the proposed trajectory occur automatically. A Control and Display Unit (CDU) page was devised for executing (or rejecting) the trajectory.

If the conflict persists until it is detected by the comparison of the state vectors, which indicates that loss of separation is predicted to occur within 5 minutes, a set of tactical-maneuver options are displayed to the pilot as a safety enhancement that permits immediate

conflict resolution with simple maneuvers. These tactical advisories are shown concurrently with the alternate FMS-route advisory, providing the pilot a quick, tactical option to clear the conflict alert while providing more time to review the proposed changes to the FMS route. An amber heading bug on the ND compass rose and a corresponding airspeed bug on the PFD airspeed tape indicate a combined heading/airspeed combination that resolves the conflict. Additionally, an amber bug on the PFD vertical speed scale indicates to the pilot an alternative vertical maneuver that also would resolve the conflict.

These CDTI design features were intended to enhance the pilot performance in autonomous operations. The conflict detection and resolution design features were intended to maximize the pilot's situational awareness of air traffic and airspace hazards while minimizing the monitoring and cognitive workload. The enhanced ND tools allowed the pilot to determine each aircraft's call sign (for possible aural or digital data link), predict its future state, avoid conflicts (using the prevention bands), and maintain self-separation using the alerting functions. These tools were evaluated to determine their usability under the multiple constraints of airborne self-separation, meeting RTAs, flying efficiently, and maximizing passenger comfort.

Air Traffic Operations Laboratory

The experiment was conducted in the Air Traffic Operations Laboratory (ATOL) at the NASA Langley Research Center. The ATOL hosts a workstation-based human-in-the-loop simulation of air traffic operations. The simulation consists of the Traffic and Events Manager (TMX), developed by NLR and NASA specifically for free-flight research, and the Aircraft Simulation for Traffic Operations Research (ASTOR), a workstation flight simulator for transport-category FMS-equipped aircraft under development at the NASA Langley Research Center. In this environment, multiple human pilot research subjects can "fly"

several ASTOR aircraft, interacting in traffic scenarios hosted by TMX. Incorporated into ASTOR are the following automation functions: conflict prevention advisories; conflict detection, alerting, and resolution; airspace hazard detection, alerting, and resolution; trajectory generation that meet RTA and performance constraints; and auto-flight systems with FCP or FMS guidance. ASTOR and TMX continuously log detailed trajectory and event data for analysis.

Experiment Objectives and Approach

The primary objective of the current experiment was to compare the two proposed operational modes applicable to airborne separation assurance in a constrained en-route environment. The experiment focused on operational aspects that relate to commercial-transport autonomous (free maneuvering) aircraft as defined by the DAG TM Concept Element 5¹⁰. A second objective was to assess the usability of the flight-deck display and user-interface design that integrated state-based and intent-based traffic information to reinforce pilot situation awareness.

This current research activity was focused on the operations of a single autonomous aircraft in en-route cruise flight with variable airspace complexity (i.e., traffic density, weather cells, SUA). Beyond the current research scope were direct interactions with the ATSP, managed aircraft, or other piloted autonomous aircraft. The study did not address multi-person flight crews, crew resource management, or voice communications. Climbs and descents of the own-ship were not studied, nor were the effects of winds or failure modes of decision-support automation or CNS infrastructure.

The comparison of the two proposed operational modes addressed the hypothesis that the strategic mode has the following characteristics relative to the tactical mode:

- Reduced the sensitivity of safety and

efficiency metrics to operational complexity

- Impacted pilot cognitive workload and time-on-task in maintaining separation
- Increased pilot confidence in the information and advisories provided by the decision-support automation
- Increased pilot acceptance of the expansion of the pilot's role to include separation responsibility

A 2-by-2 within-subjects experimental design was used to address the research objectives. The primary independent variables were operational mode (tactical and strategic) and operational complexity (low and high).

Operational complexity, for the purposes of this experiment, was assumed to be a function of traffic density and airspace hazard density. Research has shown that traffic density is correlated with operational complexity¹¹. Airspace hazard density was added as an additional relevant complexity factor of constrained operations. Although a meaningful quantification of the aggregate complexity is difficult to establish, these two complexity factors were simultaneously set at relatively low and high conditions to represent a combined operational complexity that was either relatively benign or fairly challenging. The high complexity condition, however, was not so high that reasonable trajectory solutions that met all constraints were unavailable.

Scenarios of traffic aircraft were created to represent U.S. traffic distribution and patterns that might be expected in a DAG-TM environment. An experiment region was defined by parallels 27°N and 39°N and meridians 89°W and 105°W, roughly a 600nm by 700nm area centered on Fort Worth Center. Recorded U.S. flight data from peak traffic hours on November 12, 1997 were analyzed for departure-arrival city pairs and average rates. The recorded trajectories were replaced with roughly direct routing between the city pairs, and routes

outside the experiment region were deleted. To create the background traffic (i.e., aircraft not involved in conflicts with the own-ship) for the low complexity scenarios, aircraft were launched between the same city pairs using the new routing at average rates determined from the recorded-data analysis. For the high complexity scenarios, the rates were tripled. Random high-altitude cruise levels were assigned. Polygons representing special use airspace and hazardous weather were added to the background traffic patterns. The polygons were generally small and widely scattered.

The background traffic included both autonomous and managed aircraft, and the pilots were able to distinguish between them using the traffic display, even though the conflict situations in this experiment did not directly involve managed aircraft. The purpose for including managed aircraft was to maintain reasonable consistency in the operational environment represented across multiple experiments and thereby facilitate inter-experiment data analysis. Future experiments will address issues directly related to interactions between autonomous and managed aircraft. An 80/20 ratio of autonomous-to-managed aircraft status was used, representing a reasonably matured end state for the DAG TM CE-5 concept, which does not assume 100 percent autonomous operations will ever be reached. None of the background aircraft maneuvered to resolve conflicts amongst themselves

Sixteen active commercial transport pilots participated in the study. Each flew a scenario in each of the four conditions represented in the 2-by-2 experimental design described above. The scenarios depicted the en-route phase of flight, and each scenario consisted of three segments (i.e., flight legs), and each segment contained a conflict situation. Three types of conflict situations were used in this experiment, one per segment. The conflict types are generically depicted in figure 4. The subject aircraft ("own-ship") is on the left, and the traffic aircraft ("intruder") is on the right. Solid

lines indicate intent, and the dashed line indicates a deviation from intent (i.e., a blunder). The "state-only" conflict occurs when only the state trajectories threaten a conflict. The "intent-only" conflict occurs when only the intent trajectories threaten a conflict. The "blunder" conflict is similar to the "state-only" conflict, but the intruder aircraft does not adhere to the planned trajectory change in the broadcast intent message, and the aircraft remains in conflict. These conflict types are a subset of those that could occur between aircraft. The chosen types were anticipated to have the most noticeable effect on pilot decision-making. Also, for each conflict design, the own-ship's intent and state trajectories coincided, and therefore only trajectory changes for the traffic aircraft were addressed in order to reduce the data set to a manageable size. These conflict situations were distributed in both the horizontal and vertical planes, and the initial relative orientation of the intruder aircraft with respect to the own-ship was varied.

Each of the three segments within a scenario was terminated with an RTA constraint. The subject pilot was tasked to ensure separation from the traffic aircraft while meeting the RTA constraint. The subject pilot was also told to avoid airspace hazards. In order to assess workload impact, the subject pilot was given a secondary task involving periodic monitoring and reporting of aircraft system status. Additionally, the pilot was prompted every two minutes to record his real-time assessment of workload on a seven-point scale from *very low* to *very high*.

Recorded objective measures included flight plan information, predicted and actual trajectories, event times for conflict alerting, pilot response times to alerts, conflict resolution maneuver type/initiation, RTA variances, and secondary task performance latency/accuracy (as an objective workload measure). In addition, frequency and ease of information use were collected (via electronic recordings, observations, and questionnaires) to evaluate the usability of the user interface.

Subjective measures were obtained through post-scenario interviews and questionnaires. This information was used to gain insight into pilot confidence in automation, perceived workload, and role acceptance in autonomous operations.

Preliminary Results and Discussion

Preliminary results are presented in two parts. In the first part, three case studies from the recorded data set are presented to illustrate aspects of the tactical and strategic modes as flown by subject pilots in the experiment. In the second part, subjective ratings and comments by the pilots comparing the tactical and strategic modes are given. These data represent only a fraction of the total data acquired, and further analysis and reporting of additional results is planned.

Case Studies

Some of the differences seen between the two modes of operation, tactical and strategic, will be illustrated by showing how various pilots solved the same traffic situation using the tools and procedures associated with each mode. These illustrative flights have been chosen to highlight some of the differences between the two modes and do not necessarily represent typical performance by all of the pilots. In general, it was found that when a pilot fully utilized the set of tools offered, they were able to successfully complete their tasks of maintaining separation, meeting an RTA, and operating in an efficient manner. There were only two out of 192 experiment segments where the pilot lost separation; one in each mode of operation. Interestingly, both occurred in low complexity airspace. In one case, the pilot made an altitude change without considering the conflict prevention bands on his vertical speed indicator and descended into a very near-term conflict. Minimum separation in this case was approximately 4.9 nm and 900 ft, just within the proscribed minima of 5 nm and 1000 ft. In the other case, the pilot tried to avoid a conflict by maneuvering between two approaching aircraft.

When one of these aircraft turned towards him, the pilot was unable to react quickly enough to maintain separation. Closest approach was 3.8 nm. Both situations may have developed through a lack of familiarity with the tools and experience in self-separation situations.

Case 1: State-only conflict

The first case study will illustrate how two pilots reacted to a state-only conflict. In this conflict type, the state vectors of the intruder and the own-ship are initially in conflict, i.e., threaten a loss of separation. However, the intruding aircraft has a trajectory change point (TCP) in its flight plan that occurs between three and five minutes before loss of separation which would take the aircraft out of conflict. Therefore, in a state-only conflict, if both aircraft follow their flight plans, there will be no intrusion. Both of the subject pilots in this case study saw exactly the same conflict geometry with identical background traffic and airspace hazards. The only difference was the mode of operation.

Pilot 1 operated in the strategic mode. The relevant recorded tracks are shown in Figure 5. Other background aircraft and airspace hazards are not shown. During the first several minutes of the scenario, Pilot 1 made use of his ability to view the flight plan of AA552. He could see the upcoming TCP and determined that AA552 would pass behind his aircraft and was therefore not a threat. At 6:35, Pilot 1 received a Level 1 traffic advisory on CO755, the intended intruder (Figure 5, position A). By checking the flight plan he could see that CO755 has a turn planned. The Level 1 advisory indicated that if both aircraft continue along their flight paths, there would be no loss of separation and therefore no action was required. Over the next two minutes, the pilot monitored the progress of CO755 with the flight plan displayed. Once the intruder started its turn (and the state vectors were no longer in conflict), the Level 1 advisory disappeared (position B). For the remaining seven minutes of this segment, Pilot 1 continued to scan the traffic for possible conflicts. The

pilot passed over the RTA waypoint at the proper altitude and on time. No maneuver by the pilot was required during the segment. He was able to complete all of his secondary tasks in a timely manner. His self-assessment of workload level was consistently low.

In comparison to events of Pilot 1 operating in the strategic mode, the tactical mode is illustrated in how another pilot (Pilot 2) flew the identical segment but with use of the tactical-mode tools and procedures. Therefore, he did not have the flight plan available for other aircraft; nor did he have access to a closed-loop resolution if a conflict were detected. The relevant recorded tracks are shown in Figure 6. A little over a minute into the scenario, Pilot 2 climbed 1000 ft from his starting altitude of Flight Level (FL) 320 (Figure 6, position A). This was likely in response to FX281 who was crossing 18 nm in front of the own-ship (aircraft flown by the subject pilot). At four minutes into the scenario (4:00), Pilot 2 was observed to be studying AA552 who was flying opposite direction, 14 nm to the right. At 5:20, AA552 made a 45 degree turn towards the own-ship (position B). At the turn, AA552 was nine miles in front and fourteen miles to the right of the own-ship, and its trajectory would take it well behind the own-ship. However, the unexpected course change of AA552 seemed to have unsettled Pilot 2, as he reacted to a situation that was not a threat by immediately turning 8 degrees left, away from AA552 (position C). At 6:00, Pilot 2 descended back to FL320 (position D), and at 7:00, the pilot re-engaged the FMS lateral navigation (position E). As the aircraft turned right to recapture the original flight plan, its state vector came into conflict with CO755, the intended intruder, crossing from the right at FL320. Within a few seconds, Pilot 2 turned 20 degrees more to the right to pass behind CO755 (position F). However, the intruder had an upcoming TCP (unknown to Pilot 2) that would result in a left turn towards the own-ship. As CO755 started its turn, Pilot 2 decided to ascend back to FL330, 1000 ft above CO755 (position G). Three minutes later, as Pilot 2 was trying to recapture his flight plan, there was a conflict

alert with FL (AirTran) 688. As the pilot maneuvered to the right to resolve this conflict (position H), another conflict arose on his left (TW587). One maneuver resolved both conflicts. One minute later, the pilot re-engaged FMS lateral navigation. This turn toward the flight plan put the own-ship back into conflict with both FL 688 and TW587. Pilot 2 turned back to the right to avoid these aircraft (position I). With only forty seconds before the RTA, Pilot 2 turned back towards his flight plan and started to descend to 32000 ft (position J). Due to excessive maneuvering, the pilot was unable to meet the time and altitude constraint at the final waypoint of the scenario. This pilot encountered a total of six separate alerts on three different aircraft where only one was intended. Pilot 2 also failed to complete three out of five secondary tasks (aircraft systems monitoring and reporting). His self-assessment of workload was consistently higher than Pilot 1 throughout the segment.

This case study was an illustration of a conflict type for which the preferred course of action would be to take no action other than monitor the other aircraft. Intent information was required to determine that separation would be maintained if the aircraft conformed to their intent. State information was required to provide the traffic advisory information and to monitor for conformance. The scenario illustrates a benefit of combining state and intent information in conflict alerting. Without this approach, as demonstrated in the case study, a pilot may be subjected to unnecessary problem solving.

Case 2: Intent-only conflict

In the intent-only conflict type, the aircraft state vectors are not initially in conflict. However, a planned TCP by the intruder aircraft results in trajectories that threaten a loss of separation. Conflict detection systems that use the intent information are able to detect the conflict before the TCP maneuver, whereas state-based systems would not alert the pilot until the TCP maneuver has been completed.

In the following case study, AA686 was the intended intruder and was climbing towards its planned cruise altitude that coincided with that of the own-ship. The level off would occur approximately four minutes before loss of separation.

Pilot 3 flew the scenario in the strategic mode. The relevant recorded tracks are shown in Figure 7. The pilot was initially observed to be studying the intent (i.e., the broadcast portion of the flight plans) of many of the aircraft. At 5:45 (Figure 7, position A), a Level 2 traffic alert indicated a conflict with AA686, with loss of separation to occur over seven minutes into the future. A resolution trajectory calculated by the automation was displayed to the pilot, indicating an additional waypoint that would avoid loss of separation with AA686 and return the own-ship to the RTA waypoint. Pilot 3 accepted the resolution advisory through the CDU, and the flight plan on the ND adjusted to show the modified route (position B). The alert symbology disappeared when the resolution advisory was accepted. Over the next several minutes, the pilot was observed to watch the passage of AA686 at very low ND range settings to verify that the new trajectory avoided loss of separation with AA686. This indicated that while this particular pilot was willing to accept the offered resolution, he did not fully trust the system and felt compelled to closely track the separation until AA686 had passed behind him. Pilot 3 was able to meet all given constraints.

Pilot 4 flew the same scenario as Pilot 3 but was given the tactical tools and procedures to use. The primary difference in the available tools was that Pilot 4 could only opt to see the state-vector extrapolation of each aircraft, not its current intent that, in the case of the intruder, was a target altitude of FL320. The relevant recorded tracks are shown in Figure 8. The first several minutes of the segment progressed similar to that for Pilot 3. Pilot 4 received his first alert on AA686 at 9:20 when AA686 leveled off at FL320 (Figure 8, position A). This was three and a half minutes later than Pilot 3 was alerted to the conflict. Pilot 4 elected to

immediately turn to the left (position B). Several seconds later, Pilot 4 climbed to FL330 (position C), possibly because he was unsure whether the turn would be sufficient to resolve the near-term conflict. While climbing (11:30 simulation time), an alert appeared on another aircraft flying opposite direction at FL365. Between this time and 12:40 the pilot made 3 major heading changes: right, left, and then right (position D). It is unclear why the pilot made three heading changes instead of just one. As the original intruder, AA686, passed beneath own-ship, Pilot 4 maneuvered to recapture his lateral path. At 14:30, Pilot 4 descended back to FL320 (position E). He was able to successfully maintain separation and reach the altitude and time constraints at the RTA waypoint.

In this case study, Pilot 3 benefited from the strategic mode in three ways: knowing the intentions of the intruder aircraft, having plenty of time to determine a satisfactory resolution, and having an automated system load a viable solution into the FMS for review and acceptance. Pilot 4 had little notice of the conflict, and thus may have felt pressured into making quick maneuver decisions before determining what other conflicts may result from the maneuvers. Research at the NLR has suggested that intent conflicts such as this would not normally be an issue, provided that each aircraft is equipped with a conflict prevention system such as PredASAS and that conflict-generating maneuvers (such as the level-off of AA686 in this scenario) are not permitted³. For this to be a viable approach, the conflict prevention system may need to be integrated with the FMS in order to override such maneuvers.

Case 3: Blunder conflict

The third conflict type that was presented to the pilots was a blunder, or non-conformance, conflict. The scenario geometry is similar to the state-only conflict, but in the blunder case, the approaching aircraft fails to maneuver at the TCP. A loss of separation would therefore occur if the own-ship pilot fails to maneuver. In the

experiment, the TCP was placed three and a half minutes prior to loss of separation.

The first example for the blunder conflict will be the strategic mode. The relevant recorded tracks are shown in Figure 9. For the first several minutes of the flight, Pilot 5 was observed to carefully scrutinize the traffic data with frequent changes to the ND range. At 6:30, a Level 1 traffic advisory alert on AC303 was displayed, indicating a possible threat but no action currently required (Figure 9, position A). The pilot immediately displayed the flight plan for this aircraft. At 8:45 AC303 blundered through its TCP, failing to follow its broadcast intent; the alert changed to a Level 2 alert which indicates that action will be required (position B). Two seconds later, the pilot initiated a 16 degree heading change away from the intruding aircraft (position C). Over the next three minutes, Pilot 5 made four minor heading changes to minimize the distance between himself and the intruder, essentially fine-tuning the resolution for minimum path deviation. The closest approach point was 5.1 nm (position D). After the intruder had passed behind own-ship, the pilot engaged FMS navigation to recapture his flight plan (position E). He successfully met the time and altitude constraints at the RTA waypoint. Although Pilot 5 was able to view the flight paths of the traffic aircraft, he only requested this information once, when he received the Level 1 alert on AC303. The pilot was consistently late performing the secondary task.

Pilot 6 flew the same blunder scenario in the tactical mode. The relevant recorded tracks are shown in Figure 10. As with all of the pilots, Pilot 6 spent the first several minutes scanning the traffic. At 6:30, Pilot 6 was alerted to a conflict with AC303 with a Level 2 alert (Figure 10, position A). Note that Pilot 5 received a Level 1 alert (traffic advisory with no action required) in the strategic mode at this point. The tactical mode has no Level 1 alert because intent information is not available. At the time of the Level 2 alert, Pilot 6 had just started his secondary task and decided to complete it before

resolving the conflict. This indicates that the pilot understood he had five minutes until loss of separation and did not need to act immediately. Forty-five seconds later, the pilot initiated a gradual descent to FL310 (position B). He maintained his course and continued to scan the traffic. At 12:00, the intruder passed overhead, clearing own-ship by 1200 ft. Half a minute later, Pilot 6 initiated a slow return to his target altitude (position C). He was able to easily meet the constraints at the RTA waypoint. The pilot was also very prompt with performing the secondary tasks.

This case study illustrates how the tactical mode appears better suited for blunder scenarios, particularly those where the blunder leaves little time to react. In both modes, the pilot is alerted at the same time to the possibility of loss of separation. The tactical-mode pilot is immediately instructed to resolve the conflict and is given resolution advisories to do so, allowing plenty of time to choose and execute a maneuver. The strategic-mode pilot is advised, however, not to take action prematurely but to keep watch on the traffic aircraft. Since broadcast intent would presumably be followed more often than not in an operational system, the strategic approach to reduce unnecessary maneuvering while heightening the pilot's awareness of the potential intruder may still yield benefits.

Initial Subjective Data Results

During the experimental data collection, subject pilots were asked to express their comments criticisms and suggestions regarding the controls, displays and procedures. Two questionnaires were used to collect these data: a post-simulation questionnaire and a usability questionnaire. The post-simulation questionnaire queried the pilots on the feasibility of maintaining self-separation using two operational modes (tactical vs. strategic) and two modes of airspace complexity (i.e., traffic density, special use airspace, and weather cells). The usability questionnaire was designed to evaluate the controls and displays in order to

identify their acceptability or unacceptability. Pilots were asked about the acceptability of the altitude and range filters (functions and implementation); the display clutter; the adequacy of the aircraft data block presentation; the use of color coding vs. numeric altitude information; the acceptability of the climb/descent symbology; and, the usability of the RTA (required time of arrival) symbology.

Post-simulation results

The post-simulation questionnaire asked the pilots to contrast the tactical and strategic operational modes from nine operationally specific perspectives. These included: flight safety, flight efficiency (minimized fuel consumption and time to destination), overall workload, maintaining situational awareness, identifying conflicts, resolving conflicts, alerting accuracy (no false alarms), alerting reliability (no late alarms or missed alarms), and the usefulness of the conflict prevention (no-go) bands. The pilots were asked to rate these parameters on a scale from 1 to 9, where 1 = *tactical absolutely better*, 5 = *tactical same as strategic*, and 9 = *strategic absolutely better*. The results from the questionnaire are shown in Figure 11.

These results indicate that the strategic operational mode was preferred in seven of the nine operational categories. In the areas of flight safety, flight efficiency, situational awareness, and resolving conflicts strategic was rated *much better* (8s) than tactical for the high complexity airspace. Flight efficiency was also *much better* for the low complexity operations. Strategic was rated *better* (7s) than tactical for overall workload and identifying conflicts for both low and high complexity operations. In addition, strategic was rated *better* for low complexity operations in the areas of flight safety, situational awareness, and identifying/resolving conflicts. Finally, strategic was rated *better* for high complexity operations in the usefulness of conflict prevention bands. Strategic and tactical modes of operation were only rated *same* in the areas of alerting accuracy and alerting reliability.

The small differences in the individual category ratings, and the small differences between low and high complexity should not be interpreted as necessarily significant results. Further processing of the quantitative data is required to document the significance.

In addition to these specific Likert scale (subjective rating) results, pilots were also given the opportunity to provide expanded written comments regarding tactical vs. strategic operational modes in the areas of:

- Flight safety and efficiency
- Pilot workload and attention
- Traffic information and conflict-management tools
- Acceptance of the self-separation task

Four specific questions in these areas were asked of the pilots at the end of the post-simulation questionnaire after they had completed flying 12 scenarios, six each in tactical and strategic. Responses from the 16 pilots have been reviewed, and representative quotations from the questionnaires are presented below in the form of opinions supporting strategic or tactical modes.

Please compare and/or contrast the tactical and strategic modes of operations in terms of flight safety and efficiency as traffic density and airspace hazard density (i.e., operational complexity) were varied.

Strategic mode:

“With strategic I was able to look ahead farther and more quickly assess the most critical target both in terms of time and magnitude of flight path changes required. With tactical, I felt surprised by conflicts, especially vertical.”

“Strategic is much better. Having an idea of the other aircraft’s intent allowed me to make better decisions about resolving conflict and to

avoid conflict alerts.”

Tactical mode:

“Strategic mode in high density offered too much clutter for my comfort level. I felt the tactical only was safer and more efficient because it was quicker and easier to use and required less brain RAM. As traffic density decreased, the advantages of one over the other decreased.”

“Tactical maneuvering with heading + altitude changes seemed to work best in higher complexity situations.”

Please compare and/or contrast the tactical and strategic modes of operation in terms of pilot workload and pilot attention to the separation assurance task?

Strategic mode:

“Strategic is much better – allowed me to ‘stay ahead’ rather than just react to conflict alerts.”

“Tactical placed a higher workload on me due to the fact that I was mentally computing closure rates and headings. It was better to let the computer figure it out in the strategic mode and then verify the route using the rest of the tools.”

Tactical mode:

“Tactical was less workload due to less info, but more stressing to resolve due to time element. Pilots like to be in control and know what’s coming.”

“Pilot workload increased when in strategic operation – need to pay more attention and plan further ahead.”

Please compare and/or contrast the tactical and strategic modes of operations in terms of availability, utility, and reliability of traffic information and the conflict-management

automation tools (conflict prevention, conflict detection, conflict resolution).

Strategic mode:

“Strategic allows more conflict prevention in that I could take earlier, smaller state changes, or avoid them entirely by knowing other aircraft’s intent.”

“I liked almost everything about strategic-mode tools better. I used the expected flight path a lot. However, I can see where it can potentially lead to complacency (people may deviate). Will need to always confirm that suggested resolution re-routes avoid weather and SUA.”

Tactical mode:

“Often times too much information is given, i.e., if this guy maybe does this, then you may have a conflict. Often works better when it’s in black and white. Either you do or you don’t, plus no gray area. I found tactical better/easier because less information was available.”

Please compare and/or contrast the tactical and strategic modes of operations in terms of your acceptance of the expanded responsibilities and tasks of the pilot in the En Route Free Maneuvering concept that you experienced here.

Strategic mode:

“Once you used the strategic mode and trusted it, the workload dropped. There were more opportunities to pick up targets and not rely on the ‘brain’ to make the right choices.”

“Strategic required no decision-making – simply hit the accept key and modify the airspeed which the FMS should be able to do anyway.”

Tactical mode:

No pilot comments were received that

specifically expressed a positive association between the tactical mode and acceptance of the self-separation task.

These observations support several accepted notions regarding the viability of the DAG-TM concepts and tools. First, the pilot community is diverse and it may be difficult initially to achieve universal acceptance. Second, the subject pilots in the experiment demonstrated a wide variety of understanding of the difference between tactical and strategic operational modes. There were those who trusted and accepted the strategic resolution with little or no thought to resolving the conflict presented or assuring themselves that other conflicts would not be caused by accepting the resolution. In contrast, there were those who wanted to maintain control of the aircraft, treating the strategic resolution as an advisory and preferring to accept the additional monitoring and cognitive workload associated with making the heading, altitude or speed changes manually through the FCP. Third, it is well documented that humans revert to “early learning” in stressful or high workload conditions. In this case, the pilots tended to revert to heading, altitude, and speed changes using the FCP, which they use currently in every flight, over acceptance of an automated conflict resolution flight plan with which they have no operational experience.

Usability results

This questionnaire asked the subject pilots to evaluate and comment on specific areas of the user interface design. Median results of the effectiveness of several design features are shown in Figure 12. Except where noted, the rating scale was: 1 = *completely ineffective*; 4 = *borderline*; and 7 = *completely effective*. Seven of the eight design features were rated very effective to completely effective. The orientation of the 3-digit altitude tag shown with each aircraft symbol received a rating of 5, or somewhat better than borderline. The rating was likely tempered by some of the pilots who stated they preferred all text to be horizontal.

Additional evaluation areas included the acceptability of the display clutter, the use of text vs. color coding for altitude information, and the desire for state-vector predictors. Display clutter was rated above borderline (5 on 7 point scale). Pilots were often observed to control the clutter using the altitude filter, turning the filter off for a brief scan of all traffic, and then turning it back on for decluttering. Pilots were evenly split on the reliance on altitude tail tags vs. color coding for traffic-aircraft altitude information. Ninety three percent of the pilots desired the ability to display state-vector predictors on traffic aircraft, and eighty percent wanted control over the length of the predictors. Overall, no interface issues were rated borderline or lower.

Overall, these subjective results should be interpreted as acceptance and/or approval of the control/display interface design and the information content provided. The small differences between individual ratings should not be interpreted as statistically significant results, but simply as pilot preferences based on data collected from 16 pilots at the end of 12 scenarios and 192 segments of simulated use of these tools. Further processing of the quantitative data is required to document the significance.

Conclusions

An experimental investigation was conducted to compare two possible operational modes for autonomous aircraft in a DAG-TM concept for air traffic operations under realistic constraints. The tactical mode was characterized primarily by the use of state information for conflict detection and resolution and an open-loop means for the pilot to meet operational constraints. The strategic mode involved the combined use of state and intent information, provided the pilot an additional level of alerting, and allowed a closed-loop approach to meeting operational constraints. Operational constraints included separation assurance, meeting an RTA, avoiding weather cells and SUAs, flying efficient trajectories, and maintaining passenger comfort.

In addition, CDTI design features for autonomous operations were evaluated for usefulness and effectiveness.

Preliminary results indicate that pilots in both modes were generally able to meet the operational constraints. Functional differences between the modes were evident in scenario case studies. In scenarios with conflicts based only on state vectors, pilots operating in the strategic mode were less frequently observed to maneuver unnecessarily. Under tactical situations, pilots sometimes caused several additional conflicts in their maneuvering to resolve the initial conflict. In scenarios with conflicts based initially on intent, strategic-mode pilots generally took advantage of the ability to resolve the conflict earlier than the tactical mode allowed. In blunder scenarios, the lack of intent information in the tactical mode generally resulted in resolution of the conflict before the blunder occurred.

Subjective data results indicated a consistent pilot preference for the strategic mode of operations over the tactical mode. However, supportive and constructive statements were received for both strategic and tactical modes, indicating the following conclusions. The pilot community is diverse, and it may be difficult initially to achieve universal acceptance of a common set of tools and procedures. The subject pilots had a wide variety of understanding of the difference between tactical and strategic operational modes, given the short time available for familiarization and for building experience and trust. Pilots were generally supportive of the CDTI design features supporting both operational modes and offered many helpful suggestions for further improvements. Although the strategic operational mode is relatively immature and undeveloped relative to the tactical mode, the experiment highlighted many potential benefits of the strategic mode to aid in meeting realistic operational constraints, indicating that further development and exploration of the strategic mode is warranted.

References

1. Final Report of the RTCA Task Force 3: Free Flight Implementation. RTCA, Inc., Washington D.C., October 1995.
2. NASA Advanced Air Transportation Technologies Project: Concept Definition for Distributed Air/Ground Traffic Management (DAG-TM), Version 1.0. September 1999.
3. Hoekstra, J.M., Ruigrok, R.C.J., van Gent, R.N.H.W., Visser, J., Gijsbers, B., Valenti Clari, M.S.V., Heesbeen, W.W.M., Hilburn, B.G., Groeneweg, J., Bussink, F.J.L. (2000). Overview of NLR Free Flight Project 1997-1999. Contract Report NLR-CR-2000-227, National Aerospace Laboratory.
4. Cashion, P. & Lozito, S. (1999). The effects of different levels of intent information on pilot self-separation performance. Proceedings of International Symposium on Aviation Psychology.
5. Kuchar, J. K. and Yang, L.C.: Survey of Conflict Detection and Resolution Modeling Methods, AIAA-97-3732, August 1997.
6. RTCA Special Committee 186, Working Group 6: In-progress Revision of the Minimum Aviation System Performance Standards for ADS-B.
7. McDonald, James A.; Vivona, Robert A.: Strategic Airborne Conflict Detection of Air Traffic and Area Hazards, Version 1.0. NASA Contract: NAS2-98005 RTO-29, November 6, 2000.
8. Mondoloni, Stephane; Conway, Sheila R.: An Airborne Conflict Resolution Approach Using a Genetic Algorithm. AIAA-2001-4054, August 2001.
9. Johnson, Battiste, and Bochow (1999). A cockpit display designed to enable limited flight deck separation responsibility. World Aviation Congress.
10. Phillips, Charles T (2000). Detailed Description for (DAG TM) Concept

Element 5 “En Route Free Maneuvering”,
Contract NAS2-98005 Research Task Order
41, Advanced Air Transportation
Technologies Project, NASA Ames
Research Center.

11. Mogford, R.; Guttman, J.; Morrow, S.; and
Kopardekar, P.: The Complexity Construct
in Air Traffic Control: A Review and
Synthesis of the Literature. DOT FAA
Technical Report, DOT/FAA/CT-TN95/22.
July 1995.

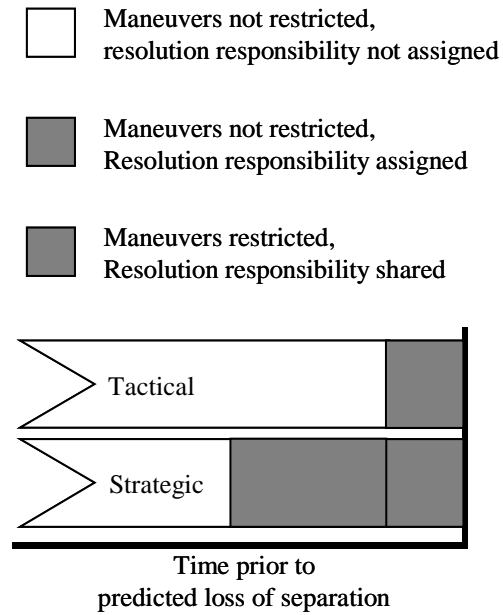


Figure 1. Effective times for maneuver and priority flight rules.



Figure 2. ND as modified to present traffic, conflict, and resolution information.

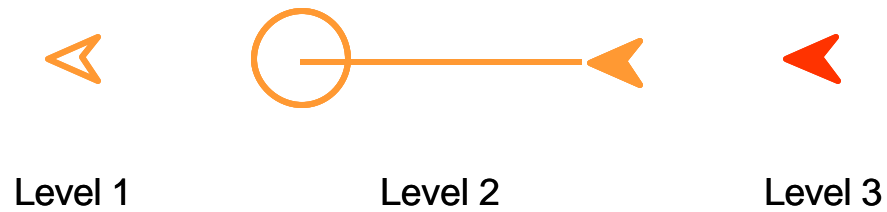


Figure 3. Traffic symbology for the alerting levels.

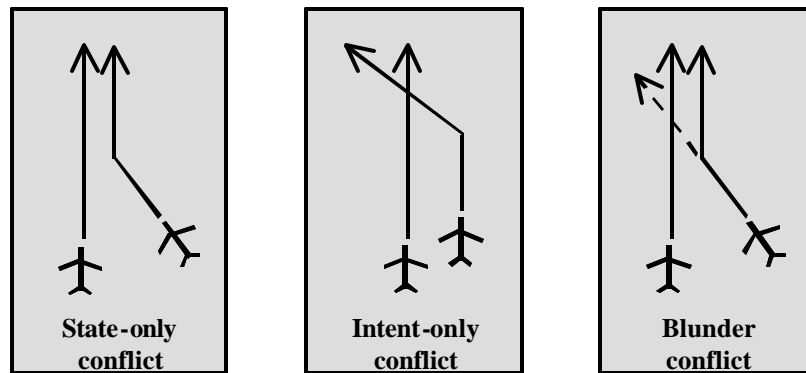


Figure 4. Conflict types investigated in the current experiment: intent only (I); state only (S); blunder (B). Intruder is aircraft approaching from the right. Diagrams are generic and do not represent the specific geometry investigated in the experiment.

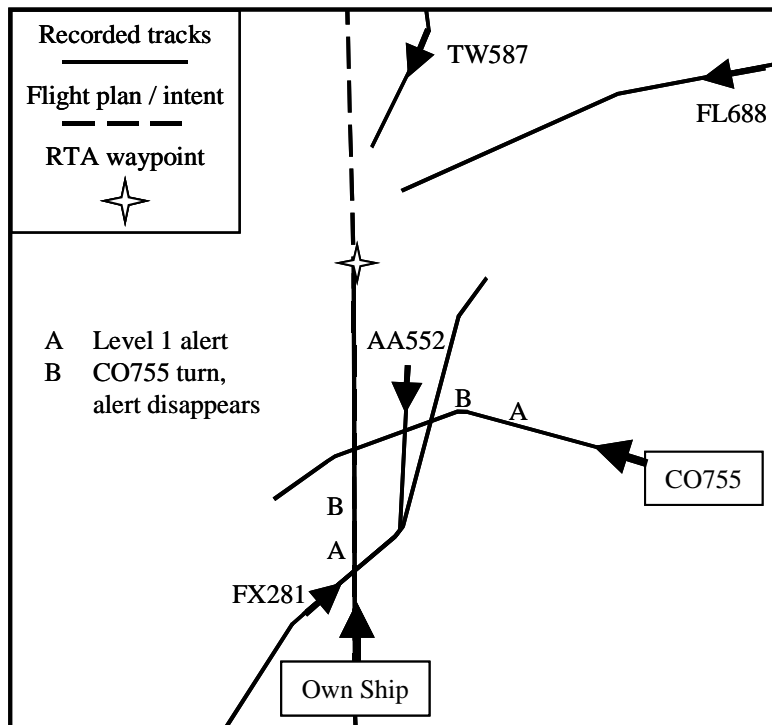


Figure 5. Recorded tracks of state-only conflict scenario flown by Pilot 1 in strategic mode.

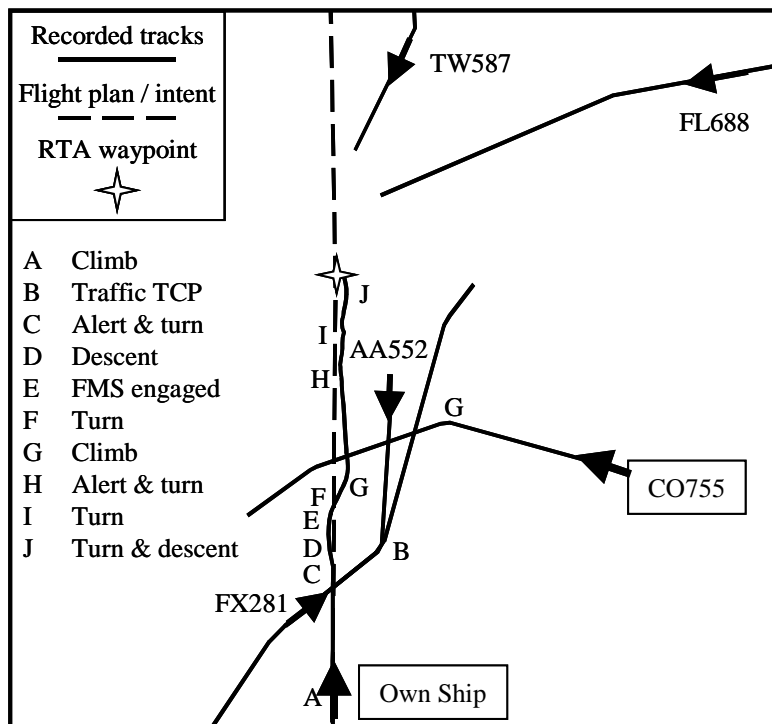


Figure 6. Recorded tracks of state-only conflict scenario flown by Pilot 2 in tactical mode.

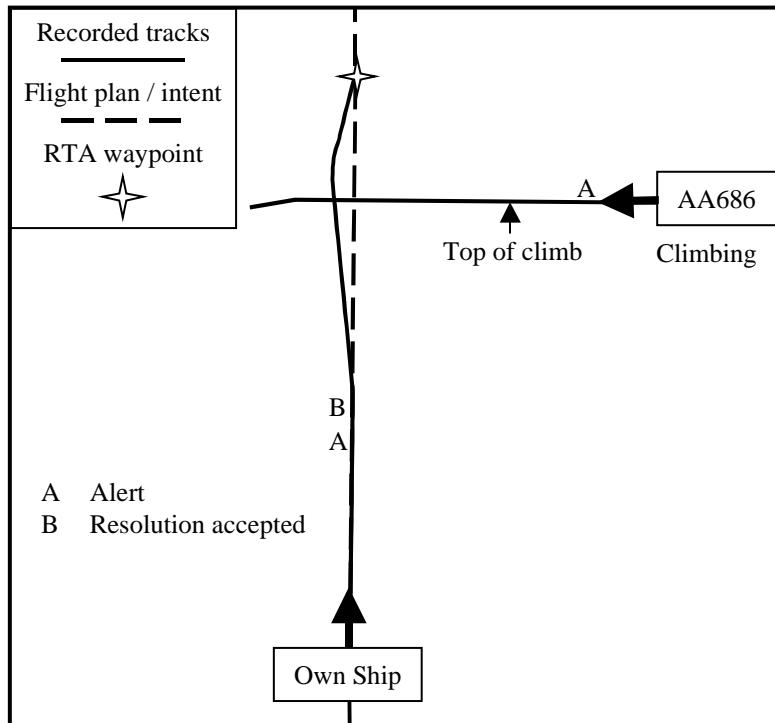


Figure 7. Recorded tracks of intent-only conflict scenario flown by Pilot 3 in strategic mode.

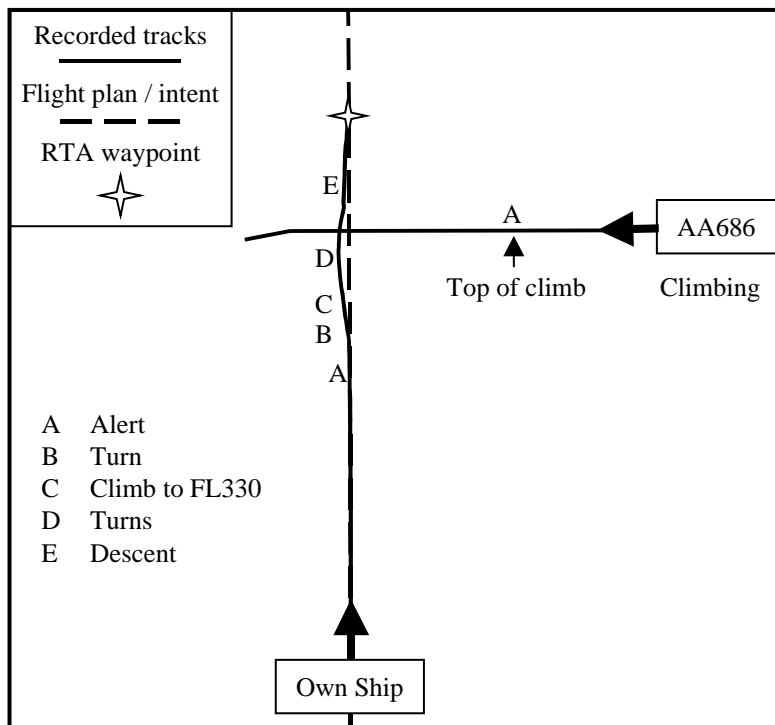


Figure 8. Recorded tracks of intent-only conflict scenario flown by Pilot 4 in tactical mode.

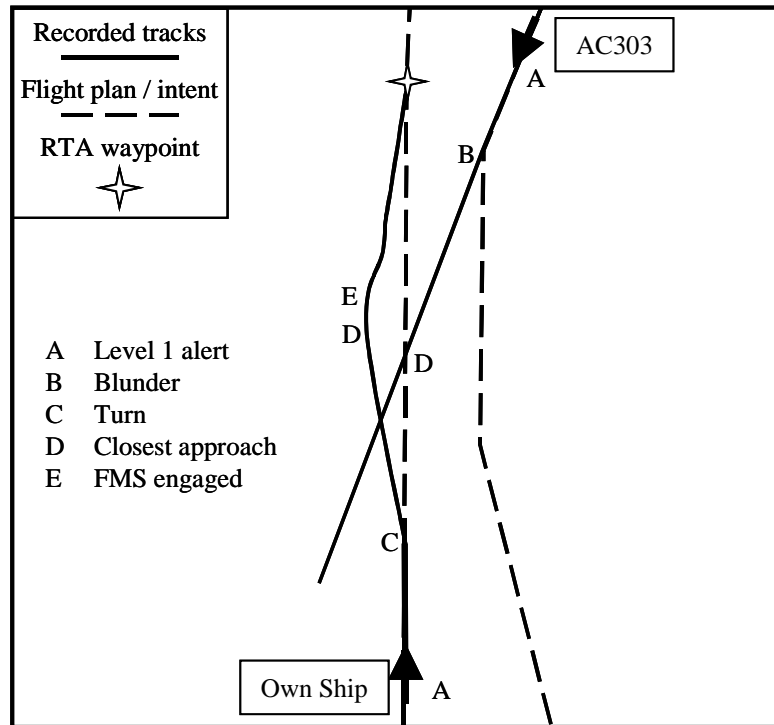


Figure 9. Recorded tracks of blunder conflict scenario flown by Pilot 5 in strategic mode.

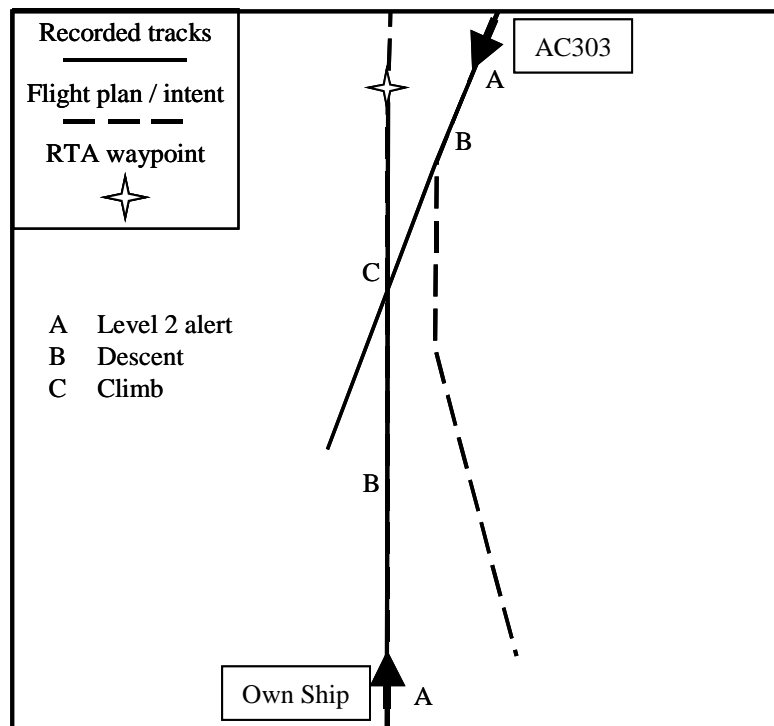


Figure 10. Recorded tracks of blunder conflict scenario flown by Pilot 6 in tactical mode.

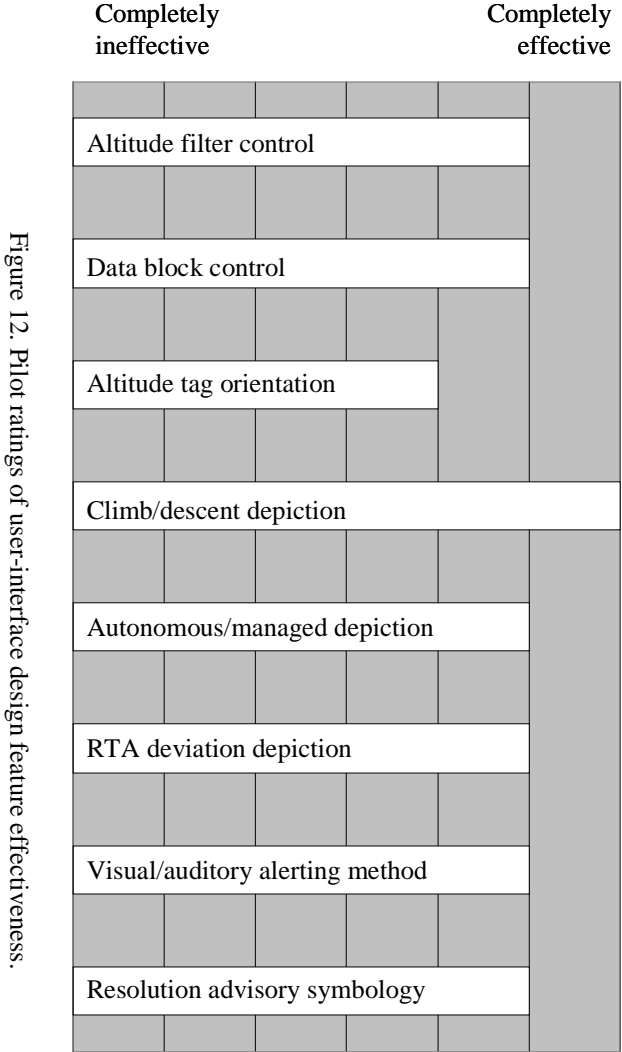
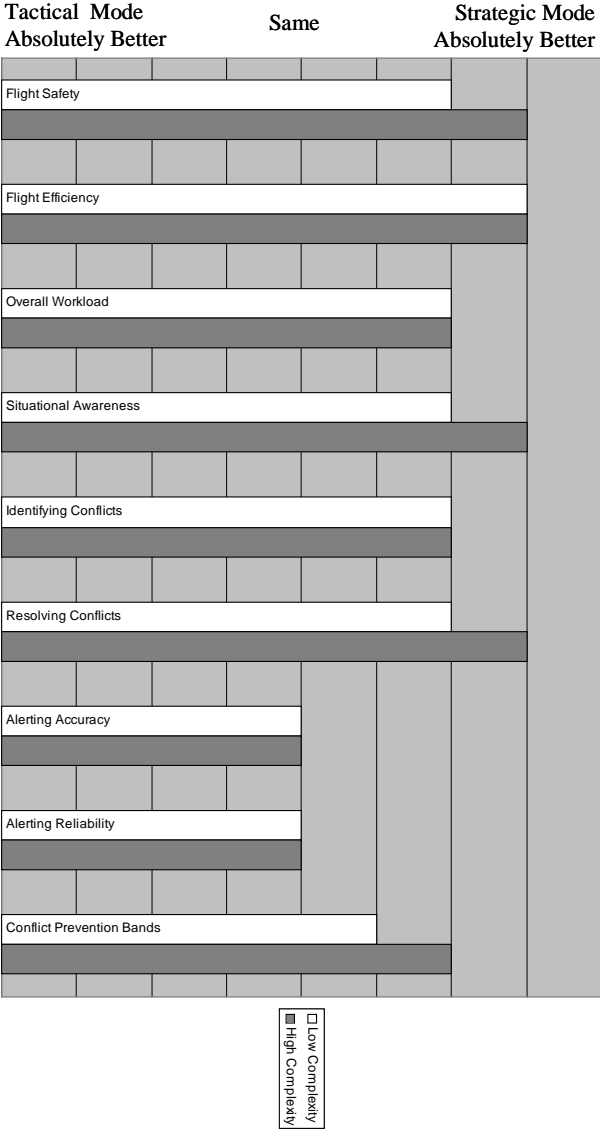


Figure 11. Pilot median ratings for comparison of tactical and strategic operational modes for autonomous operations.



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| 13. ABSTRACT (Maximum 200 words) A predominant research focus in the free flight community has been on the type of information required on the flight deck to enable pilots to "autonomously" maintain separation from other aircraft. At issue are the relative utility and requirement for information exchange between aircraft regarding the current "state" and/or the "intent" of each aircraft. This paper presents the experimental design and some initial findings of an experimental research study designed to provide insight into the issue of intent information exchange in constrained en-route operations and its effect on pilot decision making and flight performance. Two operational modes for autonomous operations were compared in a piloted simulation. The tactical mode was characterized primarily by the use of state information for conflict detection and resolution and an open-loop means for the pilot to meet operational constraints. The strategic mode involved the combined use of state and intent information, provided the pilot an additional level of alerting, and allowed a closed-loop approach to meeting operational constraints. Potential operational benefits of both modes are illustrated through several scenario case studies. Subjective data results are presented that generally indicate pilot consensus in favor of the strategic mode. | | | | |
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